AN AUTOMATICALLY CONTROLLED, INEXPENSIVE PUMP-OXYGENATOR

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SINCE the early reports of the successful development of extracorporeal circulation and open heart surgery,[8, 14] there has been widespread interest in refinement of techniques. Our group has directed its energies recently to the development of an inexpensive, self-controlled pump-oxygenator.

During the 10 years that we have been interested in experimental extracorporeal circulation, we have studied various types of pumps[10] as well as bubble oxygenators, screen- and disc-type oxygenators. At present, we prefer a rotating disc oxygenator which we have modified to suit our particular needs.

The apparatus consists of a rotating disc oxygenator originally suggested by Björk[1] and more recently, described by Kay and Cross[2, 3, 4, 11] and others,[16] combined with a roller-type pump. Venous blood is brought from the superior and inferior venae cavae to the oxygenator by gravity. Since a venous pump is not used, a significant source of trauma to the blood is eliminated. The pool of blood in the oxygenator serves as a venous reservoir so that the latter component is also eliminated. The discs are driven directly by a small fractional horse power motor at 120 revolutions per minute. Oxygenated blood leaves at the opposite end of the chamber and is carried by large-bore Tygon tubing to a roller pump. The pump then returns the blood to the arterial side through a filter. Excess blood in the opened, bypassed heart is collected by a suction tip attached to a second roller pump which delivers it to a combined defoaming chamber and bubble trap reservoir. From here, the blood is returned to the venous end of the oxygenator.

It has been shown by McCaughan and his co-workers[13] and others that most of the trauma to the blood removed from the opened heart results from excessive mixing of air with the blood in the suction pump. To minimize this effect, a control button has been placed on the suction handle which is pressed only when suction is desired. Thus the pump is turned on and off at the table, and the influx of air is minimized.

The parts of the system which are in contact with blood consist of Tygon tubing, rubber, stainless steel, and silicone-coated Pyrex glass. All of the components are autoclavable, thus ensuring sterility.

CONTROLS

In most centers where cardiopulmonary bypass is used clinically, the pump-oxygenator has been operated by either a physician or a specially trained technician or group of technicians. It is usually necessary to observe several variables continuously, and make adequate adjustments during the perfusion. Among the more important factors to be observed and controlled are (1) venous pressure, (2) arterial pressure, (3) blood level in the oxygenator, (4) flow rate, (5) blood temperature, (6) replacement of blood loss, and (7) the electrocardiogram. In addition, some centers routinely monitor (8) the electroencephalogram, (9) arterial and venous oxygen saturation, and (10) blood pH and pCO_2.
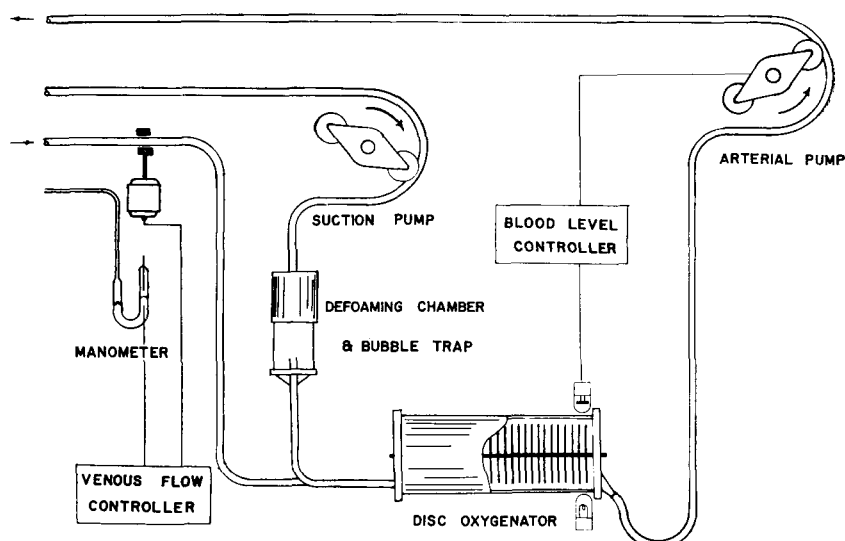

Fig. 1.—Schematic diagram of blood flow circuit.

It is generally agreed that the continuous observation and correction of the first 7 factors are necessary for a successful perfusion. By using three control systems, we are able to observe continually and maintain automatically the first 5 factors at pre-set levels. The technician is able, therefore, to direct his attention to the replacement of abnormal blood loss, under the direction of the anesthesiologist. Gibbon[8] and Kirklin[9, 12] and their associates have described the automatic control mechanisms used in the screen oxygenator which they employ.

VENOUS PRESSURE

Venous pressures are measured by passing a catheter through a superficial vein into the inferior vena cava. A sealed mercury manometer is attached to

the end of the catheter. Two electrodes are introduced into one limb of the mercury manometer and so placed to sense pressures of 10 cm. and 12 cm. of water. A motor-driven occluding clamp is placed on the main venous line between the heart and the input opening of the oxygenator chamber. Since the oxygenator is placed 75 cm. below the heart level, a greater negative pressure is developed at the opening of the venous line than can be used efficiently. A simple relay circuit is so arranged that if the venous pressure is below 10 cm. of water the motor is turned on to close the clamp ⅛ of a turn, thus reducing the amount of blood removed from the venae cavae. It then waits 8 seconds to see if this adjustment is sufficient to bring the venous pressure into the "normal" range. If it is not, it will make another correction and again wait 8 seconds. If the venous pressure is between 10 cm. and 12 cm. of water (our arbitrarily selected "normal" range), the motor-driven clamp remains in a fixed position. If the venous pressure is higher than 12 cm. of water, the circuit turns on the motor-driven clamp to open ⅛ of a turn, thus removing more blood from the superior and inferior venae cavae; it then waits 8 seconds and if the venous pressure has not fallen to "normal" it will then make another adjustment. This mechanism thus assures constant surveillance of the venous pressure and automatically adjusts it when indicated to ensure maintenance of normal venous pressure. Therefore, the same venous flow that would normally return to the heart is now being delivered to the pump-oxygenator.

BLOOD LEVEL CONTROL

Since reliability, autoclavability, and simplicity were the cardinal requirements in the design of the volume sensor, a means for obtaining a large output signal at useful power levels without complicated vacuum tube or transistor circuitry was sought. Methods that involve weighing the perfusion chamber, level sensors which require floats, or capacitive blood level pickup using the blood as a dielectric were rejected because of mechanical and electrical complexity.

A photoelectric blood level sensor was decided upon since it could operate outside the oxygenator chamber, eliminating cleaning and autoclaving problems. In addition, the complete generality possible with a photoelectric pickoff permits the direct application to a wide variety of oxygenator chamber designs with a minimum of modification. A light source and a light sensitive cell mounted on the outside of the oxygenator chamber are arranged so that a light beam passes through the walls of the chamber and falls upon the sensitive surface of a photocell in such a manner that changes in blood level varies the amount of the light falling on the cell. The electrical output of the cell is then used to control the speed of the arterial pump motor.

A major factor in the decision to use a photoelectric sensor was the recent advent of large area cadmium sulfide photocells of great sensitivity and capable of dissipating as much as 0.5 watt of electrical power. The output of

such a cell could easily be used to control a simple power amplifier required for the 1/8 horse power variable speed pump motor.

The cadmium sulfide cell is a photoconductive cell, that is, the electrical conductivity of the cell varies with the amount of light falling on it. As a circuit element, it behaves like a variable resistor. The type 6957 used in this system is a hermetically sealed unit in which the resistance varies from many millions of ohms when dark to a few hundred ohms when illuminated. The purpose of the photoelectric flow controller is to maintain a fixed volume of blood in the oxygenator throughout the procedure. This state of equilibrium is achieved by automatically adjusting the speed of the arterial pump which withdraws blood from the oxygenator. The pumping rate varies in response to signals from the sensor, the output of which is a function of the blood volume in the oxygenator. An increase in volume of blood in the oxygenator results
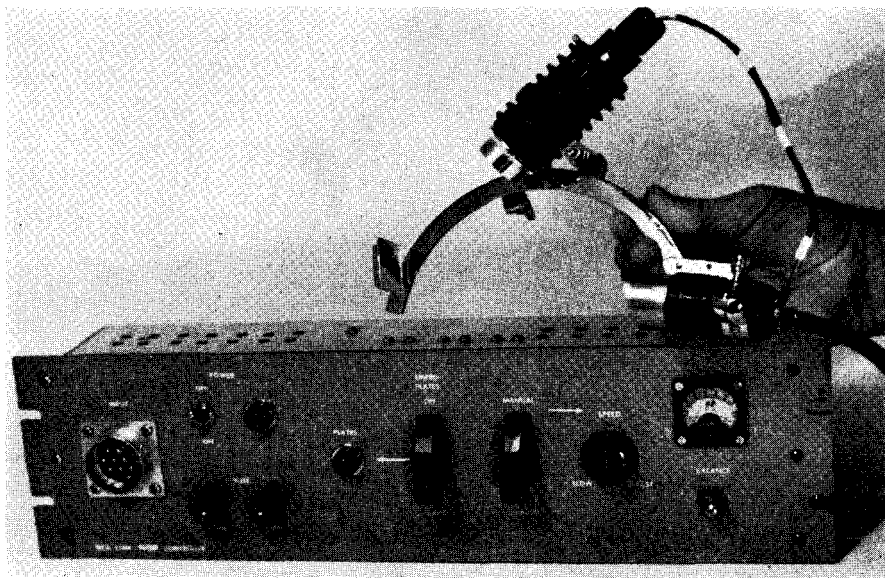

Fig. 2.—Special clamp with photoelectric cell and light source, and electronic control unit.

in an increased withdrawal pumping rate, and a decrease in volume reduces the pumping rate. The photocell is thus able to "watch" the blood level changes in the oxygenator precisely. In the 17-inch disc oxygenator, an increment of 50 c.c. of blood is detectable by the photocell. The electrical system is damped and is extremely stable. The photocell tends to select the correct pump speed continuously and maintain this speed at all times. The arterial pump output is determined by the venous return to the oxygenator. The venous return, as has been described earlier, is selected automatically to maintain venous pressures at normal levels. The blood level, then, in the pump-oxygenator is effectively locked and thus (barring abnormal blood loss from the entire system) ensures against undesirable shifts in the patient's blood volume[6, 7, 15] and automatically maintains blood pressures within normal ranges. Normal arterial

pressures assure flow rates which are consistently above 100 c.c. per kilo per minute. Thus, this one sensing device and control mechanism automatically maintains the blood in the machine at pre-set volumes, the flow rates above 100 c.c. per kilo per minute, and the arterial pressures within the normal range.

Falling arterial pressures indicate abnormal blood loss from the entire system. Blood replaced into the oxygenator will then be delivered immediately to the patient, and arterial pressure will return to the normal range. Provision is made for quickly switching the control to manual operation in case of failure,
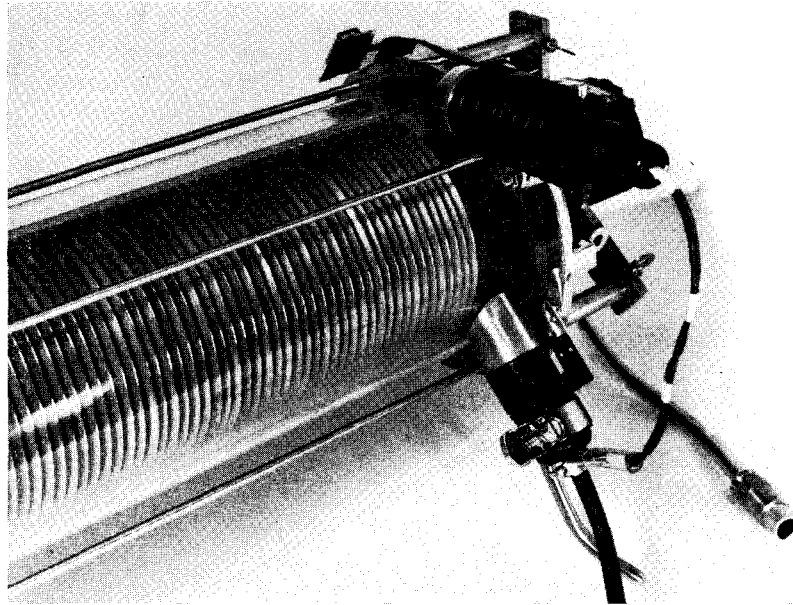

Fig. 3.—Special clamp with photoelectric cell and light source mounted on oxygenator.

by disconnecting the cell and substituting a variable resistor. The only components in the controller having finite life are two thyratrons and the excitor lamp. The thyratrons used have sufficient capacity so that if one fails, the system will continue in operation. The possibility of both thyratrons failing simultaneously is remote. Failure of the excitor lamp will cause the pump to run at full speed. In this event, the control is switched to manual operation for the remainder of the perfusion. Two excitor lamps could be built into the lamp housing for additional safety. This controller should have excellent reliability and should not be subject to sudden failure since it is simple in design and contains components that inherently have long life.

BLOOD TEMPERATURE CONTROL

It has been shown by De Wall[5] and others that it is desirable to maintain the blood in the extracorporeal circuit close to normal body temperatures. First, rapid changes in blood temperature tend to promote hemolysis of blood,

and second, oxygen is more soluble in blood at lower temperatures than at higher body temperatures. Therefore, it is possible that a saturated solution of oxygen in cooler blood in the oxygenator may come out of solution in the form of small bubbles when the blood is returned to the patient and becomes warmed. A thermistor probe is placed in a thin-walled pocket in the oxygenator chamber below the blood level. The temperature of the blood is then sensed by the thermistor and controlled by a commercially available temperature switch which turns a heater coil on and off. We have set the controller to 38° C. and are able to maintain the blood temperature within 0.5° C. The controller itself can detect changes of 1/10 of a degree centigrade.
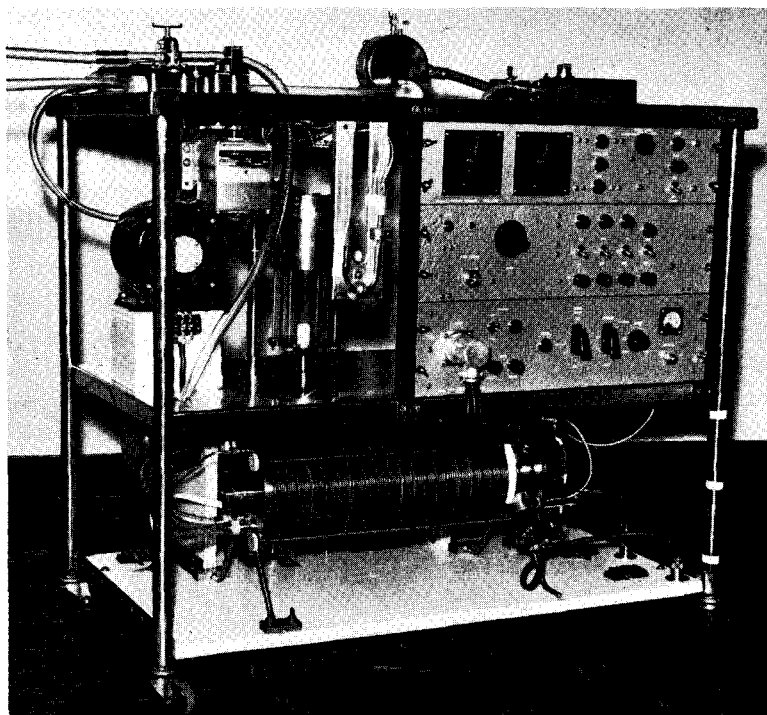

Fig. 4.—Completely assembled automatically controlled pump-oxygenator.

TECHNIQUE OF PERFUSION

The pump-oxygenator is primed with 2,500 c.c. of blood. This amount is sufficient to fill the oxygenator, the combined filter and bubble trap, the defoaming chamber, and all of the lines. Blood is circulated for a few minutes in order to be certain that all air bubbles have been removed. The arterial pump motor is turned off by a switch. The arterial and venous lines are then clamped and appropriate connections are made to the patient. To start the perfusion, the clamps are removed from the venous and arterial lines and the arterial pump motor switch is turned on. From that point on, the pump-oxygenator regulates itself. When the tourniquets around the superior and

inferior venae cavae are tightened to initiate total bypass, the increased venous return to the pump-oxygenator is automatically compensated for and all of this blood immediately returned to the patient after oxygenation. To discontinue the perfusion, one needs only to clamp the venous line. Venous return to the pump-oxygenator is then discontinued and the arterial pump will come to a stop as soon as the blood level in the oxygenator reaches its priming position.

DISCUSSION

It seems axiomatic that if a mechanism can be made to perform a given function more reliably than a human being that it should be used. A practical consideration that often enters in such a decision is the cost of such an apparatus. All of the electronic controls in our pump-oxygenator can be purchased for under $1,000.* The technician who stands by during the bypass has to be available in case of mechanical or electrical failure, in which case the pump-oxygenator can be run by manual controls. Otherwise, after the initial filling of the oxygenator with priming blood, he can devote his entire attention to replacement of unusual blood loss under the direction of the anesthesiologist.

Adjustments during the perfusion are automatically sensed and made by the machine during critical periods of change. When the perfusion is first begun, there is a tendency for the pump to overtransfuse the patient. When the venae cavae are occluded, an increased amount of blood is usually returned to the pump-oxygenator. Conversely, when the tourniquets are released, large amounts of blood can suddenly be lost from the machine. If there is unusual blood loss from the patient during the bypass, there is a tendency for blood to be lost from the pump-oxygenator. If vasopressor drugs are given, blood has a tendency to rise in the oxygenator. We feel that these abnormal shifts in blood volume are deleterious to the patient on bypass and are avoided when the blood volume in the machine is maintained at a constant level. Decreased blood level in the oxygenator decreases the efficiency of the oxygenating surface and, if the level drops low enough, may lead to air embolism. If the blood in the oxygenator rises too high, it may wet the shaft, leading to turbulence and foaming, or leak out of the shaft bearing. The apparatus that we have designed eliminates the possibility of the occurrence of these untoward manifestations.

SUMMARY

1. An improved, automatically controlled, rotating disc pump-oxygenator is described.

2. Venous pressures are continuously monitored and automatically controlled during bypass by the use of a motor-driven clamp on the venous line.

3. Blood levels, arterial pressures, and blood flows are automatically sensed and controlled with one device which is rugged, reliable, and inexpensive.

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*Available from the Teca Corporation, 80 Main Street, White Plains, N. Y.

4. Blood temperatures in the oxygenator are also controlled automatically.

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